



# **Role of binder, permeability-reducing admixtures and cracking in the watertightness of concrete structures**

A thesis by

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A thesis submitted in fulfilment of the requirements for the degree of

**Doctor of Philosophy**

Faculty of Engineering and Information Technology

School of Civil and Environmental Engineering

University of Technology Sydney

February 2017

## **CERTIFICATE OF ORIGINAL AUTHORSHIP**

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Mohammadreza Hassani Esgandani

.....

Date:

*Sincerely Dedicated to  
My Mother and Father  
Fateme and Ebrahim*

## **ACKNOWLEDGEMENTS**

I would like to express my sincere gratitude and appreciation to the individuals who supported me during my PhD studies. This research work could have not been possible without their support and guidance. I am immensely grateful to my principal supervisor, Dr Kirk Vessalas, who has provided me with intellectual guidance, encouragement, limitless support, and was always available to discuss this work. I greatly appreciate my co-supervisors, A/Prof Daksh Baweja and Prof Vute Sirivivatnanon, for their mentorship and unfailing assistance and support throughout the course of this research.

The author gratefully acknowledges the financial support provided by the University of Technology Sydney (International Research Scholarship), Sika Australia Pty Ltd (Industry Scholarship) and BG&E Pty Ltd (Industry Scholarship). My special thanks to Ms Zoe Schmidt (Sika) and Mr Joe Catanzariti (BG&E) for their valuable technical guidance and kind support.

I am appreciative to all my friends and colleagues, particularly Dr Babak Fakhim, Dr Aslan S. Hokmabadi and Dr Shamila Salek for their invaluable friendships and emotional support. Furthermore, I am grateful to the staff of the UTS and Sika concrete laboratories for their extensive assistance in conducting the laboratory experiments.

I wish to take this opportunity to express my heartfelt gratitude to my family for their priceless support and confidence in me without which I would never have achieved this moment. I am thankful my father for instilling in me the value of learning and providing me with the outstanding opportunities to follow my dreams and I am thankful to my mother for every single day that she did not have me nearby but nevertheless wholeheartedly encouraged me in my endeavour. Finally, I extend my abiding gratitude to my dear sisters for their constant support, sacrifice, and friendship throughout the years. At the end I would like to express appreciation to my beloved wife Sama for her support, encouragement and patience.

## **LIST OF PUBLICATIONS BASED ON THIS**

### **RESEARCH**

- Hassani, M., Vessalas, K., Baweja, D. & Schmidt, Z. 2013, 'Assessment of watertight concrete and role of chemical admixtures', *Concrete Institute of Australia's Biennial National Conference*, Gold Coast, Australia.
- Hassani, M., Vessalas, K., Baweja, D. & Schmidt, Z. 2014, 'Effect of chemical admixtures on water penetration of concrete', *PRO 89 - RILEM International Workshop on Performance-based Specification and Control of Concrete Durability*, Zagreb, Croatia.
- Hassani, M., Vessalas, K., Baweja, D. & Schmidt, Z. 2015, 'Benefits of water-resisting admixtures to watertight concrete', *Concrete Institute of Australia's Biennial National Conference*, Melbourne, Australia.
- Hassani, M., Baweja, D., Sirivivatnanon, V. & Vessalas, K. 2015, 'Experimental and numerical analysis of water Permeability in cracked concrete', *10th RMS Annual Bridge Conference*, Sydney, Australia.
- Hassani, M., Vessalas, K. & Sirivivatnanon, V. 2016, 'Influence of permeability-reducing admixtures on water penetration of concrete with Portland cement, fly ash and slag', *Submitted to ACI Materials Journal*.
- Hassani, M., Vessalas, K., Sirivivatnanon, V. & Baweja, D. 2016, Water penetration and self-healing properties of cracked concrete ', *Submitted to ACI Structural Journal*.

## **TABLE OF CONTENTS**

<b>ACKNOWLEDGEMENTS.....</b>	<b>ii</b>
<b>LIST OF PUBLICATIONS BASED ON THIS RESEARCH .....</b>	<b>iii</b>
<b>TABLE OF CONTENTS.....</b>	<b>iv</b>
<b>LIST OF FIGURES AND ILLUSTRATIONS.....</b>	<b>xi</b>
<b>LIST OF TABLES .....</b>	<b>xx</b>
<b>NOMENCLATURE .....</b>	<b>xxvii</b>
<b>ABBREVIATIONS .....</b>	<b>xxix</b>
<b>ABSTRACT .....</b>	<b>xxxi</b>
<b>1. Introduction .....</b>	<b>2</b>
1.1. Overview and Significance.....	2
1.2. Research Objective and Plan.....	4
1.3. Research Scope .....	6
1.4. Thesis Layout.....	7
<b>2. Background and Literature Review .....</b>	<b>10</b>
2.1. Preface .....	10
2.2. Watertight concrete structure and its applications .....	10
2.2.1. Sources of water penetration in concrete structures.....	12
2.3. Water penetration in uncracked concrete.....	15
2.3.1. Pores in concrete matrix .....	15

2.3.1.1.	Pore size ranges .....	16
2.3.1.1.	Definition of porosity .....	18
2.3.1.2.	Total porosity and permeability - what is the difference? .....	18
2.3.1.1.	Effect of w/c ratio on porosity .....	19
2.3.1.	Liquid transport mechanisms in concrete .....	21
2.3.1.1.	Adsorption .....	22
2.3.1.2.	Vapour diffusion .....	23
2.3.1.3.	Liquid assisted vapour transfer (film transfer) .....	23
2.3.1.4.	Saturated liquid flow (permeability) .....	24
2.3.1.5.	Ionic diffusion under saturated conditions .....	25
2.3.2.	Parameters influencing water absorption .....	26
2.3.2.1.	Water/cement ratio .....	26
2.3.2.2.	Curing .....	27
2.3.2.3.	Age .....	28
2.3.2.4.	Supplementary cementitious materials .....	29
2.3.1.	Parameters influencing water permeability .....	30
2.3.1.1.	Water/cement ratio .....	30
2.3.1.2.	Age .....	32
2.3.1.1.	Curing .....	32
2.3.1.2.	Supplementary cementitious materials .....	33
2.3.2.	Laboratory test methods for testing permeability and absorption .....	34
2.3.2.1.	Steady state water permeability .....	34
2.3.2.2.	Non-steady-state water penetration .....	36
2.3.2.3.	Capillary suction (absorption and sorptivity tests) .....	38
2.3.3.	On-site test methods for water penetration properties .....	41
2.3.3.1.	Initial Surface Absorption Test (ISAT) .....	42
2.3.3.2.	Gas permeability .....	42
2.3.4.	Other available standard and non-standard test methods .....	44
2.3.5.	Influence of chemical admixtures on water penetration .....	46
2.3.5.1.	Materials used as permeability-reducing admixtures .....	46
2.3.5.2.	Performance of permeability-reducing admixtures .....	51
<b>2.4.</b>	<b>Water penetration in cracked concrete .....</b>	<b>52</b>
2.4.1.	Cracking at the material scale .....	54
2.4.1.1.	Evaluation of distributed cracking .....	54

2.4.1.2.	Effect of compressive loading on permeability of concrete .....	56
2.4.1.3.	Effect of direct tensile loading on permeability of concrete.....	57
2.4.2.	Cracking at the structural scale.....	58
2.4.2.1.	Tests on a single crack.....	58
2.4.3.	Modelling the crack influence on water permeability .....	61
2.4.3.1.	Modelling liquid transfer through a single crack.....	63
2.4.3.2.	Modelling transfer through a material containing cracks .....	64
2.4.3.3.	Modelling fluid transfer through a statistically homogeneous crack medium	65
<b>2.5.</b>	<b>Self-healing properties of cracked concrete .....</b>	<b>66</b>
2.5.1.	Intrinsic healing .....	68
2.5.1.1.	Autogenous healing .....	68
2.5.1.2.	Improved autogenous healing.....	69
2.5.2.	Capsule based self-healing.....	69
2.5.3.	Vascular based self-healing .....	70
2.5.4.	Experimental techniques to verify healing .....	70
2.5.4.1.	Techniques used to examine crack healing.....	70
2.5.4.2.	Techniques used to verify recovery against environmental actions .....	71
2.5.4.3.	2.4 Techniques used to verify recovery against mechanical actions .....	73
<b>2.6.</b>	<b>Standard design procedure of watertight concrete structures .....</b>	<b>74</b>
2.6.1.	Material properties.....	74
2.6.2.	Design for durability and fire resistance .....	74
2.6.3.	Structural analysis.....	75
2.6.4.	Design for strength.....	76
2.6.5.	Design for serviceability .....	76
2.6.6.	Comparison between the crack control requirements of AS 3600 (2009) and AS 3735 (2001).....	78
<b>2.7.</b>	<b>Summary .....</b>	<b>78</b>
<b>3.</b>	<b>Research Methodology .....</b>	<b>82</b>
<b>3.1.</b>	<b>Preface .....</b>	<b>82</b>
<b>3.2.</b>	<b>Definition of watertight concrete structures .....</b>	<b>83</b>
<b>3.3.</b>	<b>Water penetration properties of uncracked concrete .....</b>	<b>84</b>
3.3.1.	Experimental work.....	84



3.3.1.1.	Test methods.....	86
3.3.1.2.	Mixing, compaction and curing.....	95
3.3.1.3.	Raw materials .....	96
3.3.1.4.	Characterisation of raw materials .....	99
3.3.1.5.	Concrete mix proportioning.....	105
3.3.1.6.	Test method validation .....	112
3.3.2.	Statistical analyses .....	113
<b>3.4.</b>	<b>Water penetration properties of cracked concrete.....</b>	<b>114</b>
3.4.1.	Experimental work.....	115
3.4.2.	Numerical analysis.....	118
3.4.3.	Finite element analysis (FEA) .....	118
3.4.3.1.	Tested material properties of concrete for FEA.....	119
3.4.4.	Shrinkage rate .....	121
<b>3.5.</b>	<b>Summary .....</b>	<b>123</b>
<b>4.</b>	<b>Results and Discussion - Water Penetration Properties of Uncracked Concrete .....</b>	<b>127</b>
<b>4.1.</b>	<b>Preface .....</b>	<b>127</b>
<b>4.2.</b>	<b>Effect of binder content on penetration properties of concrete .....</b>	<b>128</b>
4.2.1.	Water absorption.....	128
4.2.1.	Water permeability .....	130
<b>4.3.</b>	<b>Effect of binder type on water penetration properties of concrete .....</b>	<b>132</b>
4.3.1.	Compressive strength.....	132
4.3.2.	Water absorption.....	137
4.3.3.	Water absorption rate.....	139
4.3.4.	Permeability .....	141
<b>4.4.</b>	<b>Effect of w/b ratio on water penetration properties of concrete .....</b>	<b>143</b>
4.4.1.	Compressive strength.....	143
4.4.2.	Water absorption.....	145
4.4.3.	Water absorption rate.....	147
4.4.4.	Permeability .....	148
<b>4.5.</b>	<b>Effect of permeability-reducing admixtures on water penetration properties of concrete .....</b>	<b>150</b>

4.5.1.	Hydrophobic water repellent (HP).....	150
4.5.1.1.	Compressive strength.....	150
4.5.1.2.	Water absorption.....	154
4.5.1.3.	Water absorption rate.....	158
4.5.1.4.	Permeability.....	161
4.5.1.	Crystalline pore blocker (CP) .....	164
4.5.1.1.	Compressive strength.....	165
4.5.1.2.	Water absorption.....	168
4.5.1.3.	Water absorption rate.....	171
4.5.1.4.	Permeability.....	174
<b>4.6.</b>	<b>Effect of concrete age on water penetration properties of concrete .....</b>	<b>177</b>
4.6.1.	Effect of concrete age on absorption rate .....	178
4.6.2.	Effect of concrete age on permeability .....	179
<b>4.7.</b>	<b>Significance of the influencing factors – A comparison between binder type, w/b ratio and chemical admixtures .....</b>	<b>181</b>
4.7.1.	Relative influences of w/b ratio, SCMs and HP .....	182
4.7.2.	Relative influences of w/b ratio, SCMs and CP.....	184
<b>4.8.</b>	<b>Summary .....</b>	<b>185</b>
<b>5.</b>	<b>Results and Discussion - Water Penetration Properties of Cracked Concrete .....</b>	<b>190</b>
<b>5.1.</b>	<b>Preface .....</b>	<b>190</b>
<b>5.2.</b>	<b>Experimental results .....</b>	<b>191</b>
5.2.1.	Feedback controlled splitting test .....	191
5.2.2.	Cracks in concrete.....	194
5.2.3.	Crack geometry measurement by image analysis .....	196
5.2.4.	Water permeability of cracked concrete .....	199
5.2.5.	Self-healing properties of concrete .....	206
<b>5.3.</b>	<b>Numerical modelling of water permeability in cracked concrete .....</b>	<b>209</b>
5.3.1.	Numerical modelling of healing properties in concrete.....	214
<b>5.4.</b>	<b>Summary .....</b>	<b>217</b>
<b>6.</b>	<b>Finite Element Analysis of Watertight Structures .....</b>	<b>220</b>

<b>6.1. Preface .....</b>	<b>220</b>
<b>6.2. Selection of structure types for investigation .....</b>	<b>220</b>
<b>6.3. Design procedure of watertight concrete structures adopted in the current study</b>	<b>222</b>
6.3.1. Material properties for suspended roof slab and water tank in accordance with AS 3600 (2009).....	222
6.3.1.1. Compressive strength of concrete.....	223
6.3.1.2. Uniaxial tensile strength of concrete .....	223
6.3.1.3. Modulus of elasticity of concrete.....	224
6.3.1.4. Density of concrete .....	224
6.3.1.5. Stress-strain curves of concrete .....	224
6.3.1.6. Poisson's ratio of concrete .....	225
6.3.1.7. Coefficient of thermal expansion of concrete.....	225
6.3.1.8. Shrinkage strain of concrete .....	225
6.3.1.9. Strength and ductility of reinforcement .....	227
6.3.1.10. Modulus of elasticity of reinforcement.....	227
6.3.1.11. Coefficient of thermal expansion of reinforcement.....	227
6.3.2. Structural analysis of suspended roof slab and rectangular water tank in accordance with AS 3600 (2009).....	227
6.3.3. Strength design of suspended roof slab and rectangular water tank in accordance with AS 3600 (2009).....	227
6.3.4. Durability design of the suspended slab and water tank.....	228
6.3.4.1. Durability design of the suspended roof slab in accordance with AS 3600 (2009)	228
6.3.4.2. Durability design of the rectangular water tank in accordance with AS 3735 (2001)	229
6.3.5. Serviceability design of the suspended roof slab and rectangular water tank in accordance with AS 3600 (2009) and AS 3735 (2001) .....	230
<b>6.4. Finite element models and analysis.....</b>	<b>231</b>
6.4.1. Analysis software.....	231
6.4.1. Nonlinear analyses in Abaqus/CAE.....	233
6.4.2. Modelling of permeability of concrete specimen with a single crack .....	237
6.4.3. Modelling of permeability of concrete elements with multiple cracks.....	238
6.4.3.1. Crack width.....	238

6.4.3.1. Crack spacing.....	239
<b>6.5. FEA of a concrete specimen with a single crack.....</b>	<b>241</b>
6.5.1. Model geometry .....	241
6.5.2. Boundary conditions .....	242
6.5.3. Stress and strain distributions .....	243
6.5.4. Permeability .....	245
6.5.5. Model validation with experimental results.....	246
<b>6.6. FEA of a suspended roof slab .....</b>	<b>247</b>
6.6.1. Model geometry .....	247
6.6.2. Boundary conditions .....	249
6.6.3. Maximum principal stress distribution .....	250
6.6.4. Crack width.....	252
6.6.5. Permeability of cracked concrete.....	255
<b>6.7. FEA of a rectangular water tank .....</b>	<b>257</b>
6.7.1. Model geometry .....	258
6.7.2. Boundary conditions .....	259
6.7.3. Maximum principal stress distribution .....	260
6.7.4. Crack width.....	262
6.7.5. Permeability of cracked concrete.....	264
<b>6.8. Parametric study .....</b>	<b>266</b>
<b>6.9. Structural advantages of self-healing in design process.....</b>	<b>268</b>
<b>6.10. Summary .....</b>	<b>270</b>
 <b>7. Concluding Remarks and Future Work.....</b>	 <b>273</b>
7.1. Concluding Remarks.....	273
7.2. Future Work .....	277
 <b>Appendix A .....</b>	 <b>279</b>
 <b>Appendix B .....</b>	 <b>284</b>
 <b>References .....</b>	 <b>293</b>

## **LIST OF FIGURES AND ILLUSTRATIONS**

Figure 2.1 Main sources of water penetration in a typical watertight concrete structure.....	13
Figure 2.2 Two simple models of a porous material, where the pores are straight, parallel tubes of uniform width passing through the solid material: (a) one pore of radius R and (b) N=4 pores of radius $r = R/\sqrt{N} = R/2$ (after Garboczi 1995).....	20
Figure 2.3 Difference between total porosity and permeability (after Bungey & Millard 2010) .....	20
Figure 2.4 Porosity of hardened cement paste as a function of w/c ratio (after Powers, Copeland & Mann 1959).....	21
Figure 2.5 Idealised model of movement of water and ions within concrete (after Rose 1965) .....	23
Figure 2.6 Influence of the w/c ratio and initial moist curing on initial surface absorption (after Dhir, Hewlett & Chan 1987) .....	27
Figure 2.7 Average ISA test results for concrete cores from reinforced concrete tank walls (after Thomas et al. 1990).....	30
Figure 2.8 Effect of w/c ratio and binder type upon water absorption after 1.5 years of laboratory exposure (3 days moist curing) (after Parrott 1992) .....	31
Figure 2.9 Relationship between water permeability and w/c ratio for mature cement pastes (after Powers et al. 1954) .....	31
Figure 2.10 Effect of w/c ratio and initial moist curing period on water permeability (Kosmatka, Kerkhoff & Panarese 2002).....	32
Figure 2.11 Modelling of capillary filling (after Gräf & Grube 1986). .....	33
Figure 2.12 Schematic diagram of (a) permeability test configuration and (b)	

pressure cell.....	36
Figure 2.13 Example of the test arrangements for non-steady-state depth of penetration of water (BS EN 12390-8 2009) .....	38
Figure 2.14 Three principally different test set-ups for water absorption: (a) the horizontal case, (b) the infiltration case and (c) the capillary rise case (after Hall 1989) .....	39
Figure 2.15 Schematic of the procedure recommended by ASTM C1585-13 for sorptivity test (after ASTM C1585 2013) .....	40
Figure 2.16 Assembly of typical initial surface absorption test (after BS 1881-208 1996) .....	42
Figure 2.17 Theoretical air-flow into the double chamber cell (after Torrent 1992). 44	
Figure 2.18 Relation between $kT$ and Coulombs (ASTM C1202) from various independent laboratories (after Torrent, Basheer & Gonçalves 2007) .....	44
Figure 2.19 Water absorption for ordinary Portland cement (OPC) concrete with hydrophobic ingredient (HI) with an age of 28 days and a w/c of 0.40 (after Aldred et al. 2001).....	48
Figure 2.20 Permeability of concrete containing 20% Type F fly ash and crystalline admixture (after ACI 212.3R 2010) .....	50
Figure 2.21 Permeability of concrete containing 30% Type F fly ash and crystalline admixture (after ACI 212.3R 2010) .....	50
Figure 2.22 Type of cracks and their causes (after Bluey) .....	54
Figure 2.23 Relation between stress/strength ratio and bond crack length for different types of concrete loaded in compression (after Smadi & Slate 1989) .....	55
Figure 2.24 Effect of the compressive stress on water permeability of concrete (after Kermani 1991) .....	57

Figure 2.25 Schematic of BIPEDE test (after Breysse, Gerard & Lasne 1994) .....	58
Figure 2.26 Effect of the crack width on water permeability (temperature = 20°C) (after Tsukamoto & Wormer 1991) .....	60
Figure 2.27 Dependency of permeability on crack width and temperature (after Reinhardt & Jooss 2003).....	61
Figure 2.28 Crack inducing set-up and induced crack, (a) test set-up and (b) induced crack (after Park et al. 2012) .....	62
Figure 2.29 Relationship between maximum crack width and flow rate (after Nishiwaki et al. 2006) .....	67
Figure 2.30 Concept of performance recovery by self-healing (after Rooij et al. 2013) .....	68
Figure 2.31 Photomicrograph of cracked concrete under fluorescence light (after Van Tittelboom & De Belie 2013).....	71
Figure 3.1 Cutting concrete cylinders into four discs .....	86
Figure 3.2 Concrete specimens placed in desiccator for AVPV test .....	87
Figure 3.3 Initial surface absorption test.....	88
Figure 3.4 Depth of penetration of water test .....	90
Figure 3.5 Steady-state water permeability apparatus .....	91
Figure 3.6 Position the specimen in water permeability cell .....	91
Figure 3.7 Pressurised water permeability test cylinder .....	92
Figure 3.8 Concrete cubes sealed by epoxy .....	92
Figure 3.9 TORRENT permeability meter .....	93
Figure 3.10 Wenner probe.....	94

Figure 3.11 Typical shape of slumped concrete.....	94
Figure 3.12 Rotary pan concrete mixer.....	95
Figure 3.13 Curing tank .....	95
Figure 3.14 PSD of raw materials used in the current study compared to the cement PSD provided by Flyash Australia (2015) .....	100
Figure 3.15 PSD of raw materials used in the current study compared to the cement PSD provided by Struble (2006) and Celik (2009).....	101
Figure 3.16 FTIR spectrum of GP .....	102
Figure 3.17 FTIR spectrum of FA .....	102
Figure 3.18 FTIR spectrum of GGBFS.....	103
Figure 3.19 FTIR spectrum of CP .....	104
Figure 3.20 FTIR spectrum of HP .....	105
Figure 3.21 Feedback controlled splitting test setup.....	117
Figure 3.22 Feedback controlled splitting test setup.....	117
Figure 3.23 Strain gauges attached to the concrete specimens tested in compression .....	120
Figure 3.24 Strain gauges attached to the concrete specimens tested in tension .....	121
Figure 3.25 Cracking of concrete due to shrinkage (after ACI 224R 2001).....	122
Figure 4.1 Effect of binder content on absorption measured by AVPV .....	130
Figure 4.2 Effect of w/b ratio on absorption measured by AVPV – mixes with different binder content .....	131
Figure 4.3 Effect of binder content on depth of penetration of water .....	133
Figure 4.4 Effect of binder content on water permeability .....	134



Figure 4.5 Strength activity index of FA and GGBFS .....	135
Figure 4.6 Effect of binder type on compressive strength of concrete with w/b of 0.60 .....	135
Figure 4.7 Relative absorption of concretes with different binder types and w/b ratio of 0.60 .....	139
Figure 4.8 Relative absorption rate of concrete with different binder types and w/b ratio of 0.60 .....	141
Figure 4.9 Relative permeability of concrete with different binder types and w/b ratio of 0.60 .....	143
Figure 4.10 Compressive strength of concrete with different w/b and GP binder type .....	145
Figure 4.11 Absorption of concretes with different w/b and GP binder type .....	146
Figure 4.12 Absorption rate of concrete with different w/b and GP binder type.....	148
Figure 4.13 Permeability of concrete with different w/b and GP binder type .....	150
Figure 4.14 Effect of HP admixture on 28-day compressive strength of concrete with different w/b ratio and binder type.....	152
Figure 4.15 Effect of HP admixture on AVPV of concrete with different w/b ratio and binder type.....	155
Figure 4.16 Effect of HP admixture on sorptivity of concrete with different w/b ratio and binder types .....	159
Figure 4.17 Effect of HP admixture on depth of penetration of water of concrete with different w/b ratio and binder types .....	162
Figure 4.18 Effect of CP admixture on 28-day compressive strength of concrete with different w/b ratio and binder types .....	166
Figure 4.19 Effect of CP admixture on AVPV of concrete with different w/b ratios	

and binder types .....	169
Figure 4.20 Effect of CP admixture on sorptivity of concrete with different w/b ratios and binder types .....	172
Figure 4.21 Effect of CP admixture on depth of penetration of water of concrete with different w/b ratios and binder types.....	175
Figure 4.22 Initial sorptivity versus age for different binder types .....	179
Figure 4.23 Water permeability versus age for different binder types .....	181
Figure 4.24 An example of factorial analysis results for compressive strength considering the effect of w/b ratio, HP and FA .....	182
Figure 5.1 Results from feedback splitting test – load versus lateral displacement at crack opening with a predefined crack width of 0.4 mm.....	192
Figure 5.2 Feedback controlled splitting test setup.....	193
Figure 5.3 Concrete with 0.1 mm crack opening displacement.....	194
Figure 5.4 Concrete with 0.2 mm crack opening displacement.....	195
Figure 5.5 Concrete with 0.3 mm crack opening displacement.....	195
Figure 5.6 Concrete with 0.4 mm crack opening displacement and COD definition .....	196
Figure 5.7 Image analysis of cracked concrete – predefined crack width = 0.4 mm, exact crack width = 0.39 mm .....	198
Figure 5.8 Effect of crack width on flow rate in different concrete types .....	203
Figure 5.9 Effect of crack width on water permeability in different concrete types	204
Figure 5.10 Effect of crack width on flow rate – average of measurements .....	204
Figure 5.11 Effect of crack width on water permeability – average of measurements .....	205

Figure 5.12 Effect of crack width on water permeability including previous studies .....	206
Figure 5.13 Water permeability after 30 days additional curing .....	209
Figure 5.14 Measured and calculated water permeability .....	213
Figure 5.15 Relationship between crack width and reduction factor .....	214
Figure 6.1 Stress-strain curves for three different concrete types.....	225
Figure 6.2 Shrinkage strain at different ages .....	226
Figure 6.3 Effective tension area in beams and slabs, (a) slab and (b) member in tension (NTS) (after Eurocode 2 2004).....	240
Figure 6.4 FEA model geometry of concrete specimen tested in splitting tensile test (NTS) .....	242
Figure 6.5 FEA model boundary conditions of concrete specimen tested in splitting test (NTS).....	243
Figure 6.6 Stress distribution of concrete specimen loaded in splitting tensile test in X direction – predefined crack width of 0.2 mm (NTS) .....	244
Figure 6.7 Strain distribution of concrete specimen loaded in splitting tensile test in X direction – predefined crack width of 0.2 mm (NTS) .....	244
Figure 6.8 Permeability of concrete before healing – predefined crack width of 0.2 mm (NTS) .....	245
Figure 6.9 Permeability of concrete after healing – predefined crack width of 0.2 mm (NTS) .....	246
Figure 6.10 Permeability of concrete after before and after healing – experimental and FEA results – validation of FEA .....	247
Figure 6.11 FEA model geometry slab (NTS) .....	249

Figure 6.12 FEA model boundary conditions – slab (NTS) .....	250
Figure 6.13 Maximum principal stress distribution – top surface of slab (NTS) ....	251
Figure 6.14 Maximum principal stress distribution – bottom surface of slab (NTS) .....	251
Figure 6.15 Maximum possible crack width – top surface of double span suspended slab – without shrinkage deformations (NTS) .....	253
Figure 6.16 Maximum possible crack width – bottom surface of slab – without shrinkage deformations (NTS).....	253
Figure 6.17 Maximum possible crack width – top surface of slab – with shrinkage deformations (NTS) .....	254
Figure 6.18 Maximum possible crack width – bottom surface of slab – with shrinkage deformations (NTS).....	254
Figure 6.19 Initial permeability – top surface of double span suspended slab (NTS) .....	255
Figure 6.20 Initial permeability – bottom surface of double span suspended slab (NTS) .....	256
Figure 6.21 Permeability after self-healing – bottom surface of slab (NTS).....	257
Figure 6.22 Permeability after self-healing – bottom surface of slab (NTS).....	257
Figure 6.23 FEA model geometry – Rectangular water tank (NTS) .....	259
Figure 6.24 FEA model boundary conditions – water tank (NTS).....	260
Figure 6.25 Maximum principal stress distribution – water tank and its long wall with highest tensile stress (NTS).....	262
Figure 6.26 Maximum possible crack width – long wall of the water tank – without shrinkage deformations (NTS).....	263

Figure 6.27 Maximum possible crack width – top surface of double span suspended slab – with shrinkage deformations (NTS) .....	264
Figure 6.28 Initial permeability – long wall of water tank (NTS) .....	265
Figure 6.29 Permeability after self-healing – long wall of water tank (NTS) .....	266

## **LIST OF TABLES**

Table 2.1 Types of watertight concrete structures .....	11
Table 2.2 Classification of watertightness (after BS EN 1992-3 2006).....	12
Table 2.3 Classification of pore sizes according to general classification by IUPAC and to concrete science terminology(after Aligizaki 2006) .....	17
Table 2.4 Example of constant w/c and variable porosity and constant porosity and variable w/c, (after Mills 1986).....	22
Table 2.5 Water absorption (after Ollivier, Massat & Parrott 1995) .....	27
Table 2.6 Effect of the duration of curing tested by sorptivity test (after Ollivier, Massat & Parrott 1995) .....	28
Table 2.7 Effect of age on sorptivity (after Marchese & D'Amore 1990).....	29
Table 2.8 Classification of concrete permeability (after The Concrete Society 1988) .....	35
Table 2.9 Classification of concrete permeability (after The Concrete Society 1988) .....	37
Table 2.10 Maximum permissible values for AVPV in VicRoads specification (after Structural concrete Vicroads Standard Specification 2013) .....	41
Table 2.11 A list of standard and non-standard test methods .....	45
Table 2.12 Reduction in permeability of concrete using PRAs (after ACI 212.3R 2010) .....	51
Table 2.13 Experimental conditions for the study of cracking influence (after Breyse & Gerard 1997) .....	60
Table 2.14 Maximum acceptable crack width (after Vicroads Standard Specification	

2013) .....	77
Table 2.15 Limiting mean crack width (afterAS 3735 Suppl 2001).....	77
Table 3.1 Particle size distribution of 20 mm single sized aggregate (specific gravity of 2.70) .....	96
Table 3.2 Particle size distribution of 10 mm single sized aggregate (specific gravity of 2.70) .....	97
Table 3.3 Particle size distribution of uncrushed fine aggregate (specific gravity of 2.65) .....	97
Table 3.4 Particle size distribution of manufactured fine aggregate (specific gravity of 2.65) .....	98
Table 3.5 Chemical admixture classification .....	99
Table 3.6 XRF results of binders and powder admixtures .....	106
Table 3.7 Summary of mix designs of the mixes with variable w/b ratio - Scenario A .....	108
Table 3.8 Summary of mix designs of the mixes with fixed w/b ratio and binder type of GP - Scenario B .....	109
Table 3.9 Summary of mix designs of the mixes with fixed w/b ratio and binder type of GP:FA - Scenario B .....	110
Table 3.10 Summary of mix designs of the mixes with fixed w/b ratio and binder type of GP:GGBFS - Scenario B .....	111
Table 3.11 Summary of mix designs of the mixes with fixed w/b ratio of 0.50 to examine the effect of concrete age - Scenario C .....	112
Table 3.12 Summary of mix designs - validation tests .....	113
Table 3.13 Summary of mix designs and levels of variables investigated by factorial analysis .....	114

Table 3.14 Summary of mix designs for concrete tested for water permeability of cracked concrete.....	115
Table 4.1 Test results of concrete specimens with variable binder contents .....	129
Table 4.2 Compressive strength test results of concrete with different binder types .....	134
Table 4.3 Absorption test results of concrete with different binder types .....	138
Table 4.4 Absorption rate test results of concrete with different binder types .....	140
Table 4.5 Permeability test results of concrete with different binder types.....	142
Table 4.6 Compressive strength test results of concrete with different w/b ratios ..	144
Table 4.7 Absorption test results of concrete with different w/b ratios .....	146
Table 4.8 Absorption rate test results of concrete with different w/b ratios .....	147
Table 4.9 Permeability test results of concrete with different w/b ratios.....	149
Table 4.10 Compressive strength test results of concrete with HP, different w/b ratios and GP binder type.....	151
Table 4.11 Compressive strength test results of concrete with HP, different w/b ratios and GP:FA binder types .....	153
Table 4.12 Compressive strength test results of concrete with HP, different w/b ratios and GP:GGBFS binder types .....	154
Table 4.13 Absorption test results of concrete with HP, different w/b ratios and GP binder types .....	155
Table 4.14 Absorption test results of concrete with HP, different w/b ratios and GP:FA binder types.....	157
Table 4.15 Absorption test results of concrete with HP, different w/b ratios and GP:GGBFS binder types .....	157



Table 4.16 Absorption rate test results of concrete with HP, different w/b ratios and GP binder types .....	158
Table 4.17 Absorption rate test results of concrete with HP, different w/b ratios and GP:FA binder types .....	160
Table 4.18 Absorption rate test results of concrete with HP, different w/b ratios and GP:GGBFS binder types .....	161
Table 4.19 Permeability test results of concrete with HP, different w/b ratios and GP binder types .....	162
Table 4.20 Permeability test results of concrete with HP, different w/b ratios and GP:FA binder types .....	163
Table 4.21 Permeability test results of concrete with HP, different w/b ratios and GP:GGBFS binder types .....	164
Table 4.22 Compressive strength test results of concrete with CP, different w/b ratios and GP binder types .....	165
Table 4.23 Compressive strength test results of concrete with CP, different w/b ratios and GP:FA binder types .....	167
Table 4.24 Compressive strength test results of concrete with CP, different w/b ratios and GP:GGBFS binder types .....	168
Table 4.25 Absorption test results of concrete with CP, different w/b ratios and GP binder types .....	169
Table 4.26 Absorption test results of concrete with CP, different w/b ratios and GP:FA binder types .....	170
Table 4.27 Absorption test results of concrete with CP, different w/b ratios and GP:GGBFS binder types .....	171
Table 4.28 Absorption rate test results of concrete with CP, different w/b ratios and GP binder types .....	172

Table 4.29 Absorption rate test results of concrete with CP, different w/b ratios and GP:FA binder types.....	173
Table 4.30 Absorption rate test results of concrete with CP, different w/b ratios and GP:GGBFS binder types.....	174
Table 4.31 Permeability test results of concrete with CP, different w/b ratios and GP binder types .....	175
Table 4.32 Permeability test results of concrete with CP, different w/b ratios and GP:FA binder types.....	177
Table 4.33 Permeability test results of concrete with CP, different w/b ratios and GP:GGBFS binder types.....	177
Table 4.34 Initial sorptivity of concrete specimens with different binder types at different ages.....	178
Table 4.35 Water Permeability Results from ages 7 – 56 days .....	180
Table 4.36 Relative significances of variables in concrete containing HP and considering different responses.....	183
Table 4.37 Relative significance of variables in concrete containing CP and considering different responses.....	185
Table 5.1 Crack closure after unloading for different crack widths .....	193
Table 5.2 Crack geometry obtained from image analysis for concrete with predefined crack widths of 0.1 and 0.2 mm .....	198
Table 5.3 Crack geometry obtained from image analysis for concrete with predefined crack widths of 0.3 and 0.4 mm .....	198
Table 5.4 Water permeability test results – uncracked concrete (3.0 MPa water pressure).....	200
Table 5.5 Water permeability test results – Predefined crack width = 0.1 mm (0.4	

MPa water pressure).....	200
Table 5.6 Water permeability test results – Predefined crack width = 0.2 mm (0.4 MPa water pressure).....	201
Table 5.7 Water permeability test results – Predefined crack width = 0.3 mm (0.4 MPa water pressure).....	201
Table 5.8 Water permeability test results – Predefined crack width = 0.4 mm (0.4 MPa water pressure).....	202
Table 5.9 Water permeability after 30 days additional curing – uncracked concrete (3.0 MPa water pressure) .....	207
Table 5.10 Water permeability after 30 days additional curing.....	208
Table 5.11 Measured permeability, calculated permeability and reduction factor of concrete with a predefined crack width of 0.1 mm.....	211
Table 5.12 Measured permeability, calculated permeability and reduction factor of concrete with a predefined crack width of 0.2 mm.....	211
Table 5.13 Measured permeability, calculated permeability and reduction factor of concrete with a predefined crack width of 0.3 mm.....	212
Table 5.14 Measured permeability, calculated permeability and reduction factor of concrete with a predefined crack width of 0.4 mm.....	212
Table 5.15 Measured permeability, calculated permeability and reduction factor of concrete with a predefined crack width of 0.1 mm – after 30 days additional curing .....	215
Table 5.16 Measured permeability, calculated permeability and reduction factor of concrete with a predefined crack width of 0.2 mm – after 30 days additional curing .....	215
Table 5.17 Measured permeability, calculated permeability and reduction factor of concrete with a predefined crack width of 0.3 mm – after 30 days additional curing .....	

.....	216
Table 5.18 Measured permeability, calculated permeability and reduction factor of concrete with a predefined crack width of 0.4 mm – after 30 days additional curing .....	216
Table 6.1 Mechanical properties of concrete after 28 days moist curing .....	223
Table 6.2 Shrinkage strain at different ages ( $\mu\epsilon$ ) .....	226
Table 6.3 Limiting mean crack width (after AS 3735 Suppl 2001) .....	231
Table 6.4 Influence of the concrete strength grade on maximum crack width of the roof slab .....	267
Table 6.5 Influence of the shrinkage rate on the maximum crack width of the roof slab .....	268
Table A.1 Repeatability test results and standard deviations .....	281
Table A.2 Standard deviations in two confidence levels .....	282
Table A.3 Coefficient of variations in two confidence levels .....	282
Table A.4 Average coefficients of variation in two confidence levels .....	283
Table B.1 Analyses of variances - Case 1 - effect of HP in GP and FA concrete ...	284
Table B.2 Analyses of variances - Case 2 - effect of HP in GP and GGBFS concrete .....	286
Table B.3 Analyses of variances - Case 3 - effect of CP in GP and FA concrete ...	288
Table B.4 Analyses of variances - Case 4 - effect of CP in GP and GGBFS concrete .....	290

## NOMENCLATURE

$A$	Area
$a$	Absorption rate
$c$	Mass concentration
$D$	Coefficient of ionic diffusion
$d$	Depth of penetration
$D$	Thickness
$D_0$	Maximum diffusion coefficient (at infinite temperature)
$E$	Modulus of elasticity
$F$	Mass flux
$f'_c$	Characteristic compressive strength of concrete
$f_{ct}$	Tensile strength of concrete
$F_u$	Ultimate compressive strength
$g$	Gravitational acceleration
$h$	Water head
$K$	Coefficient of water permeability (cracked and uncracked material)
$k'$	Coefficient of intrinsic water permeability (cracked and uncracked material)
$kO$	Coefficient of oxygen permeability
$K_s$	Coefficient of water permeability of single crack
$kT$	Coefficient of Torrenit permeability
$L$	Length
$m$	Mass
$N$	Quantity
$P$	Pressure
$P$	Volumetric porosity
$p_w$	Pore water pressure

$Q$	Flow rate
$R$	Radius
$S$	Sorptivity
$S_r$	Crack spacing
$t$	Time
$V$	Volume
$v$	Velocity
$W$	Weight
$w$	Crack width
$x$	Distance
$z$	Elevation
$\varepsilon$	Strain
$\Delta$	Spacing
$\eta$	Viscosity
$\rho$	Density
$\sigma$	Stress
$\nu$	Porosity
$\zeta$	Reduction factor

## **ABBREVIATIONS**

ACI	American Concrete Institute
AS	Australian Standard
AWWA	American Water Works Association
BS	British Standard
CAE	Complete Abaqus Environment
COD	Crack Opening Displacement
CP	Crystalline Permeability-reducing Admixture
C-S-H	Calcium Silicate Hydrate
FA	Fly Ash
FE	Finite Element
FEA	Finite Element Analysis
FRC	Fiber Reinforced Concrete
FTIR	Fourier-Transform Infrared Spectroscopy
GGBFS	Grand Granulated Blast-Furnace Slag
GP	General Purpose Cement
HCP	Hardened Cement Paste
HP	Hydrophobic Permeability-reducing Admixture
ISA	Initial Surface Absorption
ISAT	Initial Surface Absorption Test
ITZ	Interfacial Transition Zone
IUPAC	International Union of Pure and Applied Chemistry
LVDT	Linear Variable Differential Transformer
NA	Not Applicable
OPC	Ordinary Portland Cement
PFA	Pulverised Fly Ash
PRA	Permeability-Reducing Admixture

PRAH	Permeability-Reducing Admixture for Hydrostatic Conditions
PRAN	Permeability-Reducing Admixture for Nonhydrostatic Conditions
PSD	Particle Size Distribution
NTS	Not to Scale
RC	Reinforced Concrete
RH	Relative Humidity
SAI	Strength Activity Index
SCM	Supplementary Cementitious Materials
TPT	Torrent Permeability Test
UPV	Ultrasonic Pulse Velocity
w/b ratio	Water to binder ratio
w/c ratio	Water to cement ratio
WR	Water Reducer Admixture
WT	Weight
XRD	X-ray Diffraction
XRF	X-ray Fluorescence



## **ABSTRACT**

In the absence of other deterioration mechanisms, concrete structures can be deemed to be durable and serviceable when they resist water penetration and perform their function with minimal maintenance during their service life. Watertightness of in-service concrete structures is assessed by evaluating the water penetration properties of the concrete. The main sources of water penetration in a concrete structure may arise from the concrete matrix and the presence of cracks, joints and construction defects in the concrete elements. In this study, the water penetration through the uncracked and cracked concrete matrices is investigated.

The water penetration through the uncracked concrete matrix is influenced by different parameters such as mix constitutions including the addition of the chemical admixtures, and the placing and curing conditions of the concrete. The popularity of permeability-reducing admixtures (PRAs) in producing watertight concrete has increased significantly in the last couple of decades due to their cost and time efficiency compared to the application of membrane-based waterproofers. However, the available information with regard to their performance has not been expanded at the same pace, so the reliance is mostly based on the manufacturer's data associated with experimental evidence. This study aims to evaluate the effect of common PRAs as well as the binder type, binder content, w/b ratio and maturity of the concrete on the absorption and permeability properties of the concrete. The study undertaken includes experimental research and statistical analyses to reveal the influence of the aforementioned factors and their significance. Results indicate that although the PRAs were beneficial in certain cases, the effect of binder characteristics such as binder content, binder type and w/b ratio was more pronounced than the effect of the PRAs. The efficiency of the PRAs was found to be a function of the w/b ratio, binder type and the type of test method used to evaluate water penetration.

From a design perspective, water penetration in concrete structural elements mainly results from the presence of cracks that increase water penetration by several orders

of magnitude when compared with the uncracked concrete matrix. In the current study, the effect of cracking on the water penetration properties of concrete was investigated experimentally and numerically. Controlled cracks with predefined widths of 0.1 mm to 0.4 mm were induced in concrete specimens through feedback-controlled splitting tensile tests. The permeability characteristics of cracked concrete specimens were determined and compared with those of uncracked concrete specimens. Crack healing was investigated over time in concretes with and without PRA additions. Numerical relationships were developed between crack width and water penetration. Results indicate that the water penetration in the cracked concrete is largely influenced by the crack size and geometry, and the flow rate is cubically related to the crack width. The induced cracks in all types of concrete evaluated were found to heal under the conditions examined when these crack widths were below 0.1 mm. The cracks in concretes containing crystalline PRAs were found to heal at widths of up to 0.2 mm.

To predict the water penetration in concrete structures, finite element analysis was employed to model the permeability of cracked concrete under service loads. The permeability of the concrete specimens was modelled and validated against the experimental results. Subsequently, two common types of watertight concrete structures including a roof slab and a rectangular water tank were analysed. The areas in these concrete structures with high potential for water penetration due to cracking (before and after self-healing) were predicted via finite element models. Results were in agreement with the experimental test data carried on the cracked concrete specimens.